

A picture is worth a thousand words—and it costs . . . *

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INTRODUCTION

The present is a critical, frustrating, and exciting time in the history of computer graphics. A dozen significant trends are developing in the same field of view. Several much-needed trends are not developing. The technology is changing so rapidly that four generations of graphical systems are in operation at once. "Computer graphics" means different things to different people. This is therefore a difficult session to "introduce."

Perhaps the most important introductory remark to make about the session is that the papers that follow this one do not attempt to cover the topic of computer graphics. They are *in* computer graphics, not *on* it. In this paper, I shall not try to cover the topic, either, but I shall take a brief look at the over-all field and try to sketch out enough of a map to provide an orientation and context for the papers that follow. In the process, I shall unburden myself of a few deep convictions.

There are three main efforts in computer graphics. The first is to improve the capability of graphical displays to represent things and processes. This capability extends into dimensionality, verisimilitude, complexity, and motion.

The second main effort is to improve the interaction between men and computers through graphics, to improve graphics as a medium of communication. It is important to distinguish between communication and representation. Both involve languages, but not in the same way.

The third main effort is to develop applications of computer graphics. Applications run the gamut from

computer-aided composition of printed pages to computer-aided design and dynamic modeling.

All the foregoing pose problems of computer-system design and are energized and/or inhibited by economics.

This paper will deal, then, in an introductory—and necessarily sketchy—way with representational capability, communication and interaction, applications, computer-system design, and economics—all in the context of computer graphics. Because the art is long and the time fleeting, the paper will consist essentially of observations and assertions within those areas rather than reviews or analyses of them.

Representational capability

Although most computer graphics is limited to arrangements of points and line segments, together with perhaps a hundred elementary figures (characters), computers are of course capable of processing and displaying areal pictures replete with graded lightness (brightness) and varied hue (color). The work of Stockham¹ at the M.I.T. Lincoln Laboratory and the University of Utah illustrates the versatility of the computer in handling still pictures with gray scale. Stockham scans a low-contrast photograph into the computer memory, takes the logarithm of every lightness coefficient, applies a la Ernst Mach a second-spatial-derivative operator to each neighborhood of coefficients to yield a new coefficient for the central element of the neighborhood, then takes the antilogarithm and displays the resulting picture. Detail not visible in the original stands out clearly in the processed picture. But the processing requires many seconds for a picture with a million elements, and Stockham's kind of picture processing is not kinematic or "on-line interactive" in the present state of the technology. Nor does the computer "understand" the

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picture in the sense of forming a structured model of the pictured scene in which the various objects and their parts are represented separately in a hierarchy. Thus in Stockham's application we see an emphasis of high precision in representation and processing at a sacrifice of speed and structuredness.

The work of Evans, Warnock,² and their colleagues at Utah starts with a structured model in the memory of the computer, rather than a high-information-content photograph at the input scanner. They have developed methods of processing that yield a halftone-like picture, in color, with "hidden lines" suppressed—in a small fraction of the computer time that would have been required two years ago. At the present time, however, even with the Utah methods, one cannot process and display areal (e.g., halftone) pictures fast enough to produce moving pictures in real time. He can go to slow-time frame-by-frame generation of film, or he can schematize, or both.

The technology for handling schematized pictures and diagrams—made up of points, line segments, and characters—has advanced markedly during the last two years. Roberts³ described some of the basic ideas, involving homogeneous-matrix representation and perspective transformation. In the work that won them the prize at the Fall Joint Computer Conference, Robert Sproull and Ivan Sutherland⁴ developed hardware that very rapidly transforms selected parts of a model in the computer's memory to a line drawing on the cathode-ray screen. The hardware rejects all the parts of the model—a large two-dimensional drawing or a three-dimensional scene—that would not be seen through a given window, and it produces the magnifications or perspective transformations and the clippings or trimmings at the window frame necessary to display just what would be seen through the window. It does all that fast enough to display 3000 lines flicker-free. The "3000 lines" refers to what is actually displayed; there can be many more lines than that in the model. The hardware handles curved lines and surfaces. It works hand-in-glove with the Warnock hidden-line algorithm, which works on schematized (linear) as well as areal displays, and the hardware is applicable to, and will decrease the processing time required for, areal displays.

The foregoing dealt with actually two-dimensional displays of two- and three-dimensional objects and scenes. There are interesting ways to make the displays perceptually, or even actually, three-dimensional. The method of calculating and presenting two slightly different "stereo" views is well known. So are methods based on the "kinetic depth effect," which present a single, changing view. When successive two-dimensional

cross sectional images are projected in rapid sequence upon a moving screen, the eye, because of its persistence, sees the composite three-dimensional image. See Traub.⁵ The computer can control the settings of a matrix of push rods to make a three-dimensional surface, a histogram rising from a plane. And, of course, it can synthesize a hologram.

Of those and other approaches to 3-D, the most exotic appears to be one demonstrated by Ivan Sutherland and associates at Harvard last year. The computer has a model of a situation in its memory, and it receives signals from sensors that tell it where the observer is and in what direction his head is oriented. With the aid of hardware described earlier, the computer then displays the part of the modeled situation that the observer would see. The display is projected from a small cathode-ray tube on the observer's head through a semi-silvered mirror into one of the observer's eyes, and the observer sees the displayed part of the situation out in front of him. He can look around and walk around—and always see what he would see if he were in the modeled situation. When I saw the demonstration, the hardware was not finished, and the situation was just an outline room with windows, a door, and a geometrical piece of statuary. Even at that, it was quite an adventure. Given situations defined by thousands of line segments, one could surely create some exciting experiences—and probably some very significant ones. As Sutherland has pointed out, the "physical" laws of the modeled world can be determined by the programmer. They can change with time. They can even depend upon the observer's behavior. Elsewhere, the possibility of creating a direct four-dimensional experience has been discussed. See Licklider.⁶ I shall not go through it again here, but let me say that it will be intellectually at least as exciting to perceive and explore a synthetic 4-D world as to perceive and explore a merely actual, merely 3-D moon.

Most of the capabilities of representation described in the foregoing are characteristic at present solely of expensive equipment and are regarded by many as esoteric. I shall say something about that under the heading, *Economics*, but for the moment let it direct our attention to the other end of the spectrum. Among the most significant developments as judged from a practical point of view, certainly, are computer setting of type, computer-aided preparation of diagrams and graphs for the printed page, computer-aided composition of advertisements, computer-aided generation of films, off-line production of graphics (as with curve plotters and as with the Stromberg-Carlson 4020), and fast on-line display of alphanumeric data and text.

Communication and interaction

It is of course very important in computer graphics to be able to represent things and processes accurately and in detail. I think it is more important to be able to represent them in proper structural organization. I think it is still more important for computer graphics to be an effective medium of communication. Good one-way communication is good, but good two-way communication—good graphical man-computer interaction—is better.

Now, as the history of art shows, and as Huggins and Entwisle⁷ will emphasize, and as I hoped Don Hatfield would develop in depth in this session, the representation with the greatest verisimilitude is not often the best means or medium of communication. Good graphical communication is more a matter of linguistic expression than it is of pictorial reproduction. Unfortunately, we in the computer world do not know much about the language, and unfortunately not many of us are trying hard to find out about it. Obviously, it does not have much to do with programming languages. It probably does have something to do with data structures. But mainly it is the art of expressing ideas through configurations and manipulations of signs and symbols. Let me call that art an essential extension of computer graphics and then leave the topic to Huggins and Entwisle. I like their approach to it, insofar as the one-way language—computer to man—is concerned.

In my assessment, however, communication is essentially a two-way process, and in my scale of values, interaction predominates over detail, gray scale, color, and even motion. In my judgment, the most important problem in computer graphics is that of establishing excellent interaction—excellent two-way man-computer communication—in a language that recognizes, not only points, lines, triangles, squares, circles, rings, plexes, and three-way associations, but also such ideas as force, flow, field, cause, effect, hierarchy, probability, transformation, and randomness. Nowhere, to the best of my knowledge, is such interaction approached in a broad problem area at the present time. The nearest things to exceptions are the graphical computer-programming interactions of Ellis and Sibley⁸ at RAND, the partly graphical, partly alphanumeric on-line augmentation of Engelbart's⁹ intellect at Stanford Research Institute, and the graphical explorations in architecture of Negroponte¹⁰ at M.I.T. It is very frustrating to me that five and a half years have elapsed since Sketchpad passed its milepost without bringing more progress in man-computer interaction at the level of ideas and concepts.

It seems unlikely that work in computer-aided design of devices and structures will lead to the advances I am

hoping for. Computer-aided design of complex systems or processes might do it. I like the name, "interactive dynamic modeling," for the art. I want to see develop a kind of combination of computer-aided design à la Sketchpad and computer-program simulation à la on-line GPSS or OPS—in which the modeler and the computer engage in a high-level graphical interaction to formulate and test hypotheses for the solution of difficult problems that are not amenable to straightforward logico-mathematical formulation, that involve more synthesis than analysis, more discovery than proof. Well, it is not much to have the name. I wish I had the method, the language, the software, and the hardware.

Man-computer interaction of course presupposes computer-input devices (as well as languages) to mediate the communication from man to computer. The man should be able to signal the computer in a natural and synergic way, as by pointing and marking with a stylus while enunciating control words or phrases. He should be able to write or draw on the same surface as the computer. I shall not develop this part of the discussion beyond saying that one can appreciate the problem after he has read the transcript of a good blackboard lecture and then later (and separately) seen photographs of the blackboard. "Chalk plus talk" is an excellent medium. Neither chalk nor talk alone carries much information. The communication must therefore lie in the coordination.

Applications

At present, it appears that three very different classes of application of computer graphics are successful: (1) routine applications in the field of publishing (e.g., *Chemical Abstracts*) that yield printed pages as primary output and at the same time retain the information in computer-processible form for updating or secondary exploitation; (2) routine applications throughout business and industry (e.g., airline ticketing, display of stock quotations) that involve fast on-line display of alphanumeric data or text from computers; and (3) "cream" (and often highly nonroutine) applications in government and industry (e.g., military command and control, space-mission control, seismic prospecting for oil) in which the premium on being first or best is very high or in which the required results cannot be achieved any other way. The first two do not require sophisticated graphic capability. The third requires and can afford very sophisticated capability.

If and when there exists and is available the kind of computer graphics I referred to as "interactive dynamic modeling," computer graphics will become a part of thinking and problem solving and decision making

wherever those functions are carried out. Design will of course be a major application area: design of all kinds of systems and processes—space, urban, transportation, manufacturing, military—as well as devices and structures. Management of government and business will use graphics in its “command and control.” Applications will abound in research and development and in medicine. But the application area *par excellence* will be education. Almost anything not involving muscular skill that needs to be explained and demonstrated can be explained and demonstrated best with the aid of interactive computer graphics. For the sake of brevity, I shall leave that as a simple assertion in need of proof by demonstration.

The trouble is, all those applications that depend upon a significant augmentation of the human intellect (to use Engelbart’s phrase) demand a level of computer graphics as sophisticated as that required for the “cream” applications mentioned earlier—or even more sophisticated.

The field is ready for and cultivating simpleminded applications in which computer graphics will do faster or less expensively things that can already be done without it, but the field is not yet ready to accept the challenge of “mind expansion.” That carries us to the economics again—which we shall examine very shortly.

System design

The prevailing idea in computer-system design for graphics is that graphical display places too heavy a demand for processing to be handled by the (or a) main, central processor and that there should, therefore, be a satellite graphical processor for each graphics console or cluster of graphics consoles. At present, the satellite processor is usually a small general-purpose computer augmented by a display processor.

The design of the satellite processor is itself an interesting problem. Is it to be programmed once and for all and viewed thereafter as just part of the hardware, or is it to be thought of as remaining a programmable computer? Is its display processor to do nothing but display, or should it be able to call display subroutines and perhaps handle the integer arithmetic of indexing? Sutherland and Myer¹¹ have observed the tendency for the display processor to evolve into a general purpose computer and then to need a subordinate display processor, and they have determined how and where to stop the potentially infinite regress.

The aspect of system design that I think has not been thought through clearly concerns the division of tasks between the central computer and the satellite computers. There is a watershed: either all the satellites will be near the central computer, or at least one will be

remote. If all are near, why should each satellite computer have a separate memory? That leads to a wasteful transferring of data from one memory to another. Why shouldn’t the satellite processor be precisely a display processor and address a block of the main memory?

If the satellite is remote, of course it cannot address the main memory directly; it must have a memory of its own. If one satellite is remote, all the satellites should have memories of their own, for it is most important to preserve homogeneity for the sake of simplicity.

Now we come to Bert Sutherland’s Dictum: “Think Network!” Even if you plan to have all the graphics consoles in the same room as the main computer, treat them as if remote—because one day soon it will be desirable to admit a remote satellite into the system—or you will want to share software with a system that has remote satellites.

The key problem then becomes the division of tasks and the specification of the interface between the central and the satellite computers. That problem must be solved in such a way that the satellite does not pester the central computer continually, yet the user should feel that he is interacting directly with the central machine. I doubt that there is a good solution.

Economics

There are of course two main kinds of cost: (1) the cost of the equipment; (2) the cost of developing the methods and preparing the programs. The bad thing is that for sophisticated computer graphics both are very great. The good things are that the hardware costs tend to drop rapidly, once they start dropping, and that, as soon as there is replication of hardware, the software costs increase much less rapidly than the number of hardware systems in which the software is used. That is elementary, but it is very important and evidently not well enough recognized.

During the 25-year history of digital computing, the costs of arithmetic units, control units, and processible memories have halved approximately every two years. On-line terminals have not had such a “long” history—at least not in significant quantity—but it appears that some of the simple keyboard-and-cathode-ray-tube consoles that are coming into use in time-sharing systems dropped from about \$13,000 to about \$6,500 in the year between the last two Fall Joint Computer Conferences. If some are priced at \$5,000 in the exhibit area of this conference, it will suggest that, for a time, one class of equipment will be halving in cost each year.

I do not want to make too much of such gross trend analysis, even though it does point to the source of

much of the magic of our field, and I certainly shall not base anything on a halving of cost each year. However, the question of optimal research lead time is a very important question, and it needs an answer. When should we develop the kind of computer graphics that will most strongly augment the intellect? When should we start if we want to have it ready when it will be affordable? In their paper, Huggins and Entwisle⁷ will call educational application of interactive computer graphics, based on time sharing, an "economic absurdity" and suggest that the facilities be used to generate educational films. Insofar as operations are concerned, I agree with them. But what about research?

As basis for a rough calculation, let me take a system that I think would make an excellent base for a computer graphics laboratory. A few months ago I determined the cost of a graphics-oriented PDP-10 computer with 256K words of 2.5-microsecond memory, 15 million words of disk storage, 16 consoles with storage-tube displays, and quite an assortment of supporting equipment. It was about \$700,000. If it were used 8 years, with an average of 10 consoles active over the 24-hour day, the cost per console hour would be \$1. Double that to cover maintenance, operation, supplies, and overhead, and you have \$2 per console hour to use as an argument that you could be within hailing distance of economic operation now if you had the programs.

As I see it, the advances in methodology and software required to achieve the kind of computer graphics and the kind of interactive dynamic modeling I hope for will require about as much research effort and time as several laboratories have devoted to interactive computing since 1961. If we look ahead to 1977, and assume hard work in the interim, I think we can count on a fairly good methodological and programming capability. If the halving-every-two-years rule held, the over-all equipment cost would be about 12 cents per console hour in 1977. It need not be that low to support all the educational and personal applications that it should support. Other applications—in management, research, medicine, etc.—would have become economic earlier, of course.

My conclusion—which is of course as tentative and open to bias as the foregoing estimates, and perhaps as simpleminded—is that now is the time to push forward

with research in the areas of computer graphics that people call expensive, sophisticated, esoteric, and exotic. I think that they are the areas in which lie the real promises of significant improvement in our intellectual processes. If we do not push forward with research in those areas now, we shall find ourselves with a magic lantern that we don't know how to rub.

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